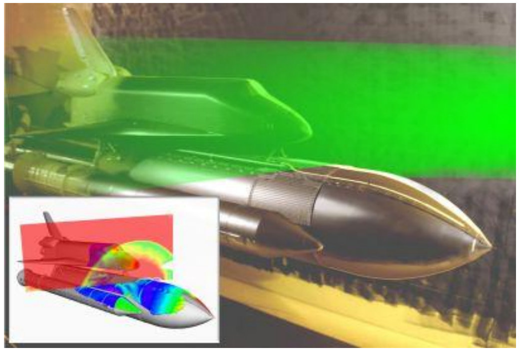

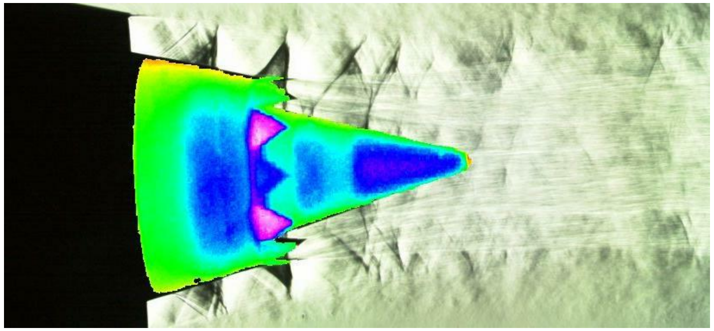

The Advancement toward Unsteady Pressure/Temperature-Sensitive Paints

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Outline
Pressure/Temperature-Sensitive Paint (PSP, TSP)

- Introduction
- Basic Principles
- Measurement Systems
- Data Reduction / Calibration
- Unsteady PSP Coating Development
- Examples – PSP & TSP
- Summary

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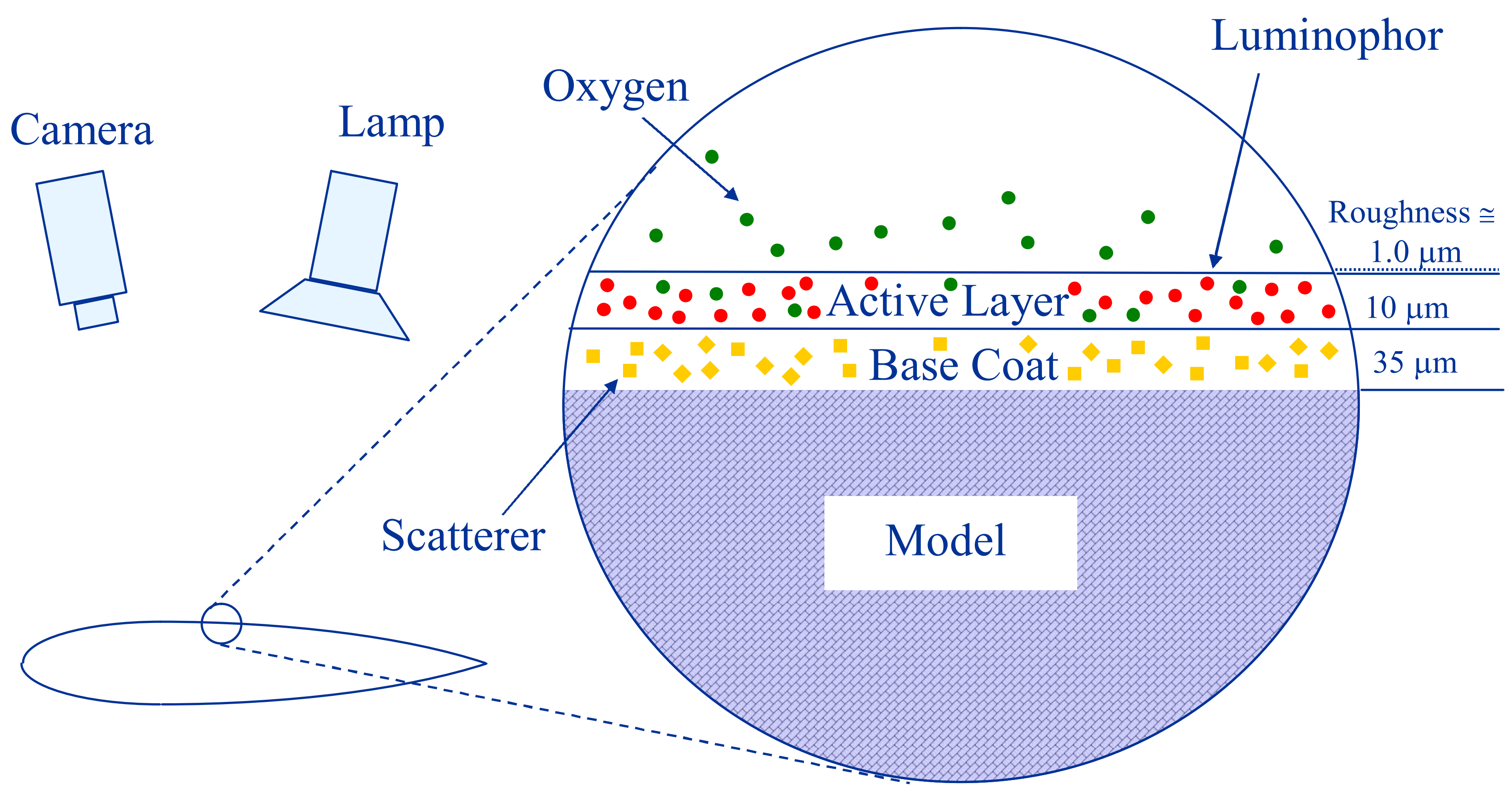
Introduction

- **Pressure/Temperature Measurements**
- Pressure and temperature measurements are primary measurements made in most practical aerodynamic testing or basic fluid mechanics experiments. Surface pressure & temperature measurements are used for:
  - Identifying specific flow phenomena (boundary layer separation, shock wave impingement, heat transfer, etc) that are not easily measured by standard pressure tap or thermocouple measurements
  - Validation of computational codes, image based data can be mapped to CFD grids for comparison
  - Loads calculations by integration of the surfaces pressures

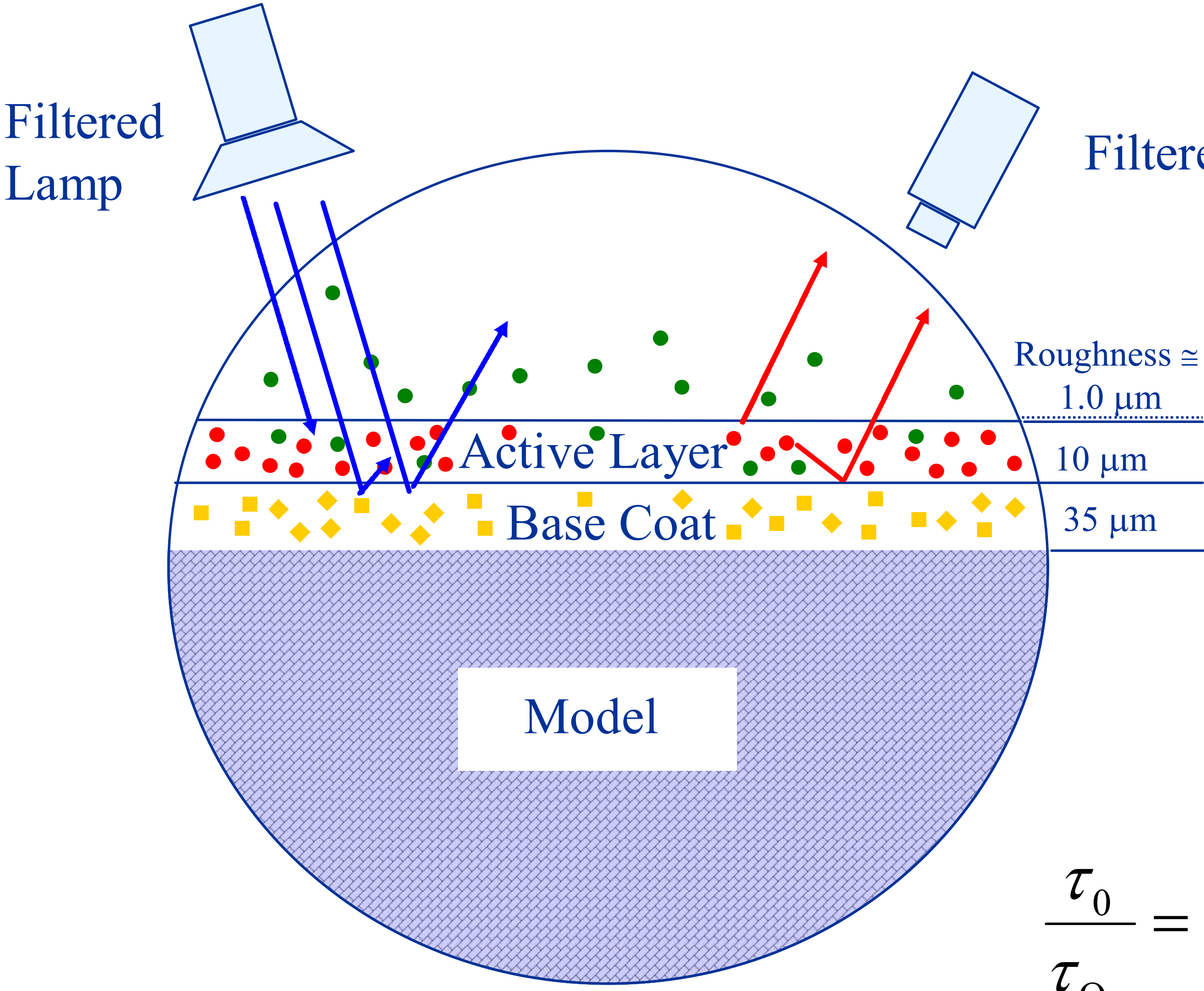
Anatomy of a polymer PSP



Binder and basecoat effects

- Luminophor molecules typically mixed into a binder for application to the test surface.
  - Provides a matrix to adhere luminophor to surface.
  - Allows control of quenching rate by limiting oxygen permeability.
  - Increases temperature-sensitivity.
  - Reduces response time.
  - Adds thickness and roughness to test article.
- Binder is typically applied on top of a reflective basecoat
  - Reflectivity enhances signal from painted surface.
  - Covers high contrast marks or mixed materials
  - Chemically isolates luminescent paint from test surface.

Paint Response



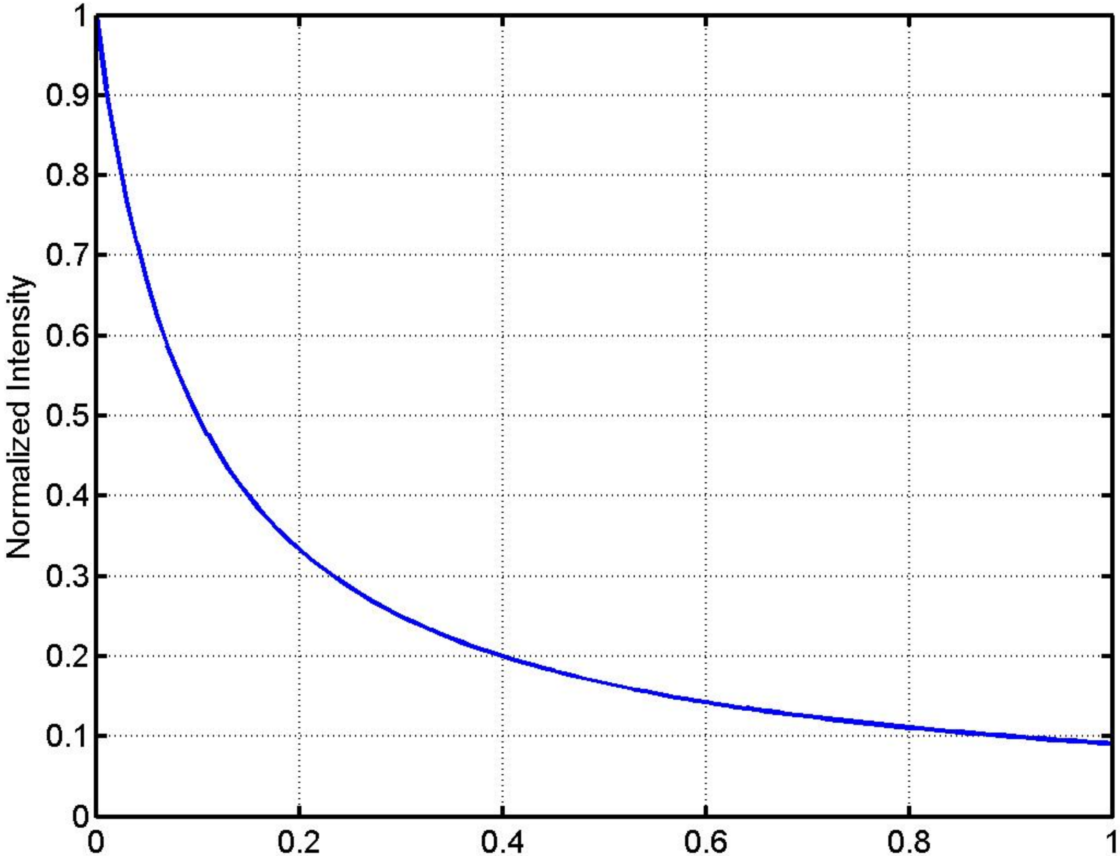
TSP

$$I_0 / I = e^{a\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$

PSP

$$\frac{\tau_0}{\tau_{O_2}} = \frac{I_0}{I_{O_2}} = 1 + K_{SV} P_{O_2}$$

Typical non-linear intensity response of PSP



Normalized Oxygen Concentration / Normalized Pressure

Aging and decay of PSP

- Photodegradation
  - Quenching generates singlet state oxygen, which decays by luminescence at λ = 1240 nm with a lifetime ~ 40 μsec.
  - Singlet oxygen is highly reactive, and oxidizes surrounding materials.
  - Oxidation of luminophor decreases paint brightness by an amount proportional to product of illumination, O_2 concentration (pressure), and time.
  - Paint pressure and temperature sensitivity relatively unaffected.
- Contaminants
  - Skin oils on surface increase photodegradation
  - Some scatterers (TiO2) seem to increase photodegradation rate
- Typical brightness loss is 20-30% over two weeks testing

Effect of temperature on luminescence

- Quenching rate is temperature-dependent due to binders oxygen permeability usually being temperature-dependent.
- If oxygen permeability is not temperature-dependent, the paint's pressure response will not be temperature-dependent, although it's overall brightness may still be. Such paints are known as "ideal".
- Luminescence activation energy process is temperature dependent
- Temperature-dependence of TSP usually not affected by binder.
- Range of temperature sensitivities of typical paints 0.2 - 5%/°C

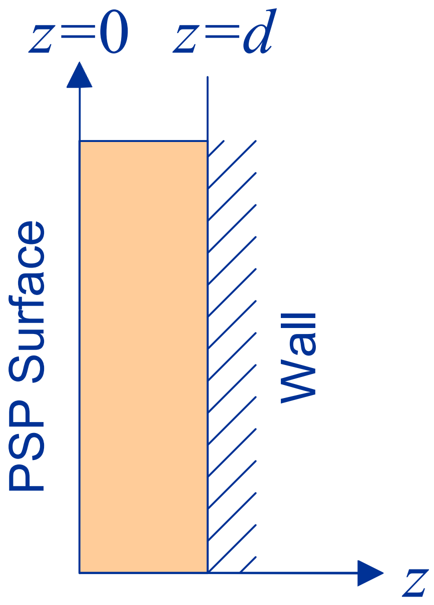
PSP Diffusion Model

- One-dimensional diffusion is assumed.
- Assume luminophore quenching is much faster than diffusion time scale.
- Adsorption of gases onto the porous surface is neglected.
- Paint layer is assumed to be optically thin.
- Uniform luminophore distribution is assumed.
- Diffusivity assumed constant.

PSP Diffusion Model

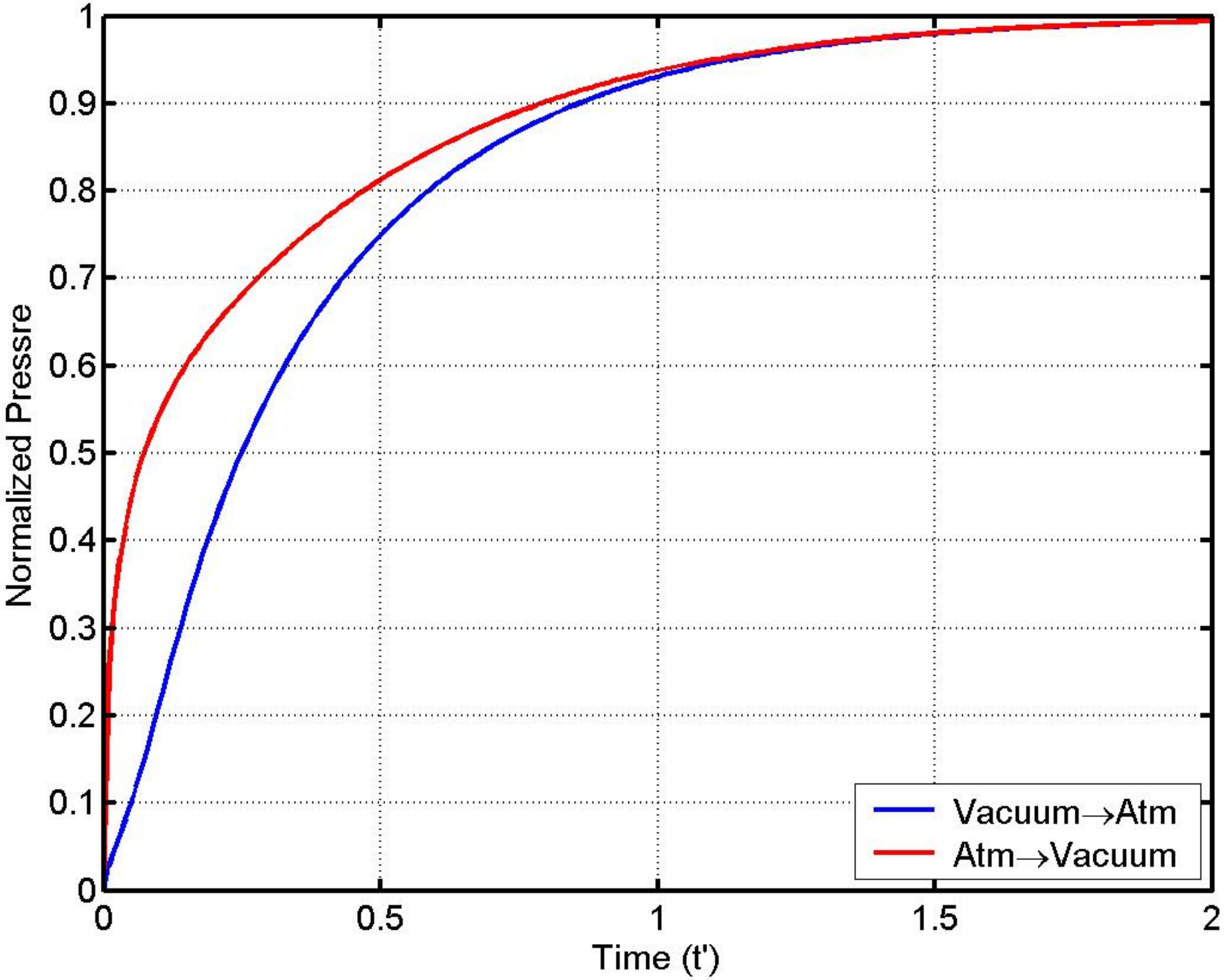
- Luminescence lifetime (typically 100 nsec to 50 μsec) ultimately controls time response.
- Time response in binder set by diffusion of oxygen.

$$\tau_{poly} = \frac{4d^2}{\pi^2 D_{O_2}}$$



Pressure Step-Response in polymer PSP

Modeling results: PSP response has a delay to an increase in pressure.



Common Sensors

- Imaging sensors
  - Cooled CCDs
    - Frame transfer: Preferred for low noise, high quantum efficiency
    - Interline transfer: Useful for lifetime measurements
    - Intensified: very fast gating, high gain, high fixed pattern and noise
  - CMOS - high noise, low quantum efficiency
  - NTSC/PAL format cameras - too noisy, limited dynamic range
- Non-imaging sensors
  - Photodiodes (PD): Preferred for low noise
  - Photomultiplier Tubes (PMT): Noisier under typical PSP conditions, some usefulness when very fast time response is needed

Intensity Methods

- Requires two readings, a reference at constant pressure (wind-off) and an unknown data point (wind-on)
- Ratio of intensities I_{REF}/I is inversely proportional to the air pressure
- The excitation and detection systems must be spectrally separated, ($>10^{-6}$ attenuation in stop band)
- Simplest technique, most sensitive
- Very sensitive to motion between wind-off and wind-on data
- A long period of time can elapse between reference and data images resulting in significant changes in emission of the paint, light stability, etc that cannot be normalized by the reference condition.

Intensity Methods

Imaging Techniques

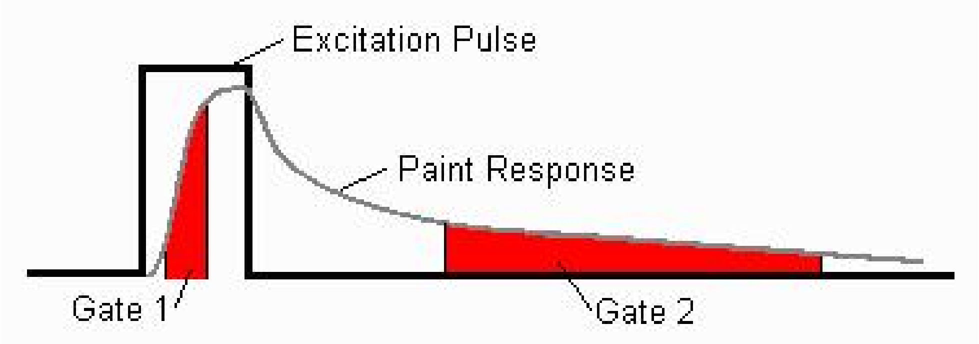
- Most aero data is taken during steady state conditions with constant illumination
- Steady state data extracted from a pulsed synchronization illumination with a periodic experiment (rotating)
- Dynamic data from a pulsed synchronized illumination with a periodic experiment with time delay off of a trigger signal

Point Techniques

- CW laser and PD/PMT to get time history data at a single point both steady and unsteady data
  - Laser can be stationary or scanned

Time-resolved Methods

- Easiest to do with a point measurement, but can use time resolved cameras to measure lifetime decays of the probe molecules.
- Point measurements require a pulsed light source and detector (PMT, PD)
- Time resolved imaging requires a double pulse type experiment to measure the decay times (gated camera, interline transfer camera capable of multiple flash integration).



$$\tau = f(P, T)$$

Luminescent lifetime τ

Time-resolved Methods

Benefits:

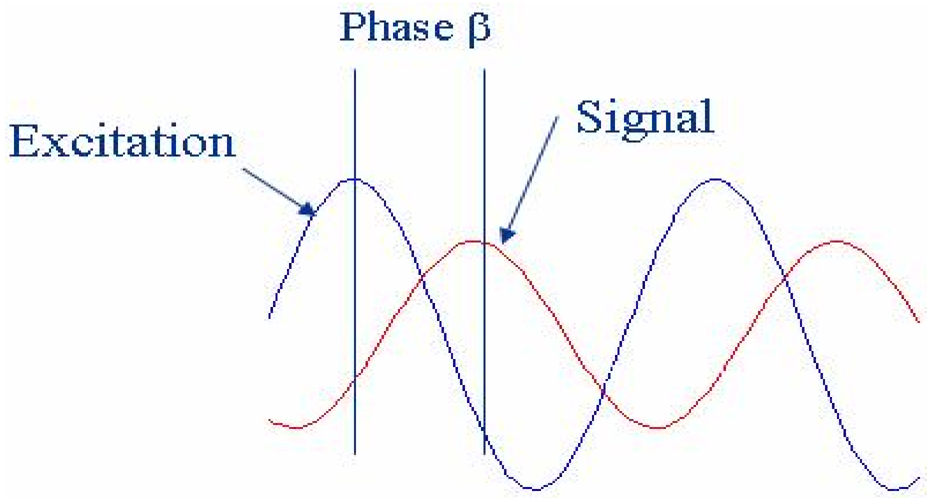
- Eliminates the need for aligning two images since the pair of images are taken at the same condition relatively close in time
- Determination of pressure and temperature from a single probe using 3 gates

Disadvantages:

- Camera noise is significantly higher
- Paints have tended to be more spatially noisy from lifetime differences between molecules (homogeneity problem).

Frequency-resolved Methods

- If modulation frequency is fixed, then the phase angle $\beta = f(P, T)$
- Phase angle can be measured directly with a lock-in amplifier
- Phase delay can be measured using two images from a camera locked in phase to the excitation, the second image is acquired out of phase



Calibration

- A-priori Calibrations
  - Paints are typically calibrated in a cell that varies pressure and temperature and has a reference measurement – this calibration is used when no on-model instrumentation exists
- In-situ Calibration
  - Uses standard on-model instrumentation to calibrate the paint/images in place (pressure taps or thermocouples)
  - Compensates for differences from reference data, spatial temperature differences (PSP) are averaged among all the points used to generate a calibration
- In practice both calibrations are typically used

Data reduction

- Multi-step process of converting light intensity measurements in the image plane to pressures
  - Detector corrections (bias, flat-field, etc)
  - Correct for real-world effects (motion, bending, temperature, etc)
  - Mapping image plane to model plane
  - Calibration
- Custom or commercial software is available

Unsteady pressure / temperature

Challenge: Unsteady measurements – Usually a very small unsteady portion of an already low light level process

For imaging applications

- Must use multiple strobe integration to have enough light for meaningful measurements – periodic process

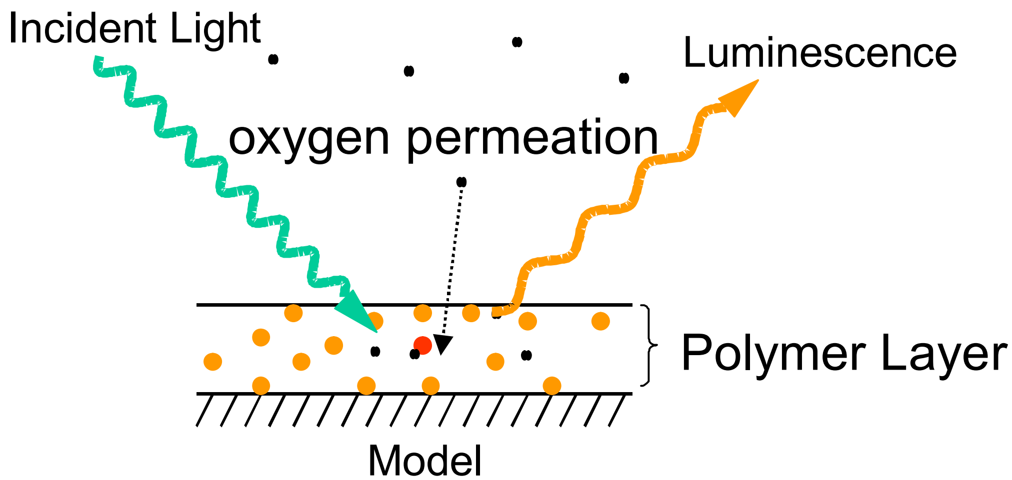
Point measurements

- Photodiodes or PMT are used with laser or LED excitation
- Laser can be scanned or potential multiple spots at the same time

Objective of developing an porous surface

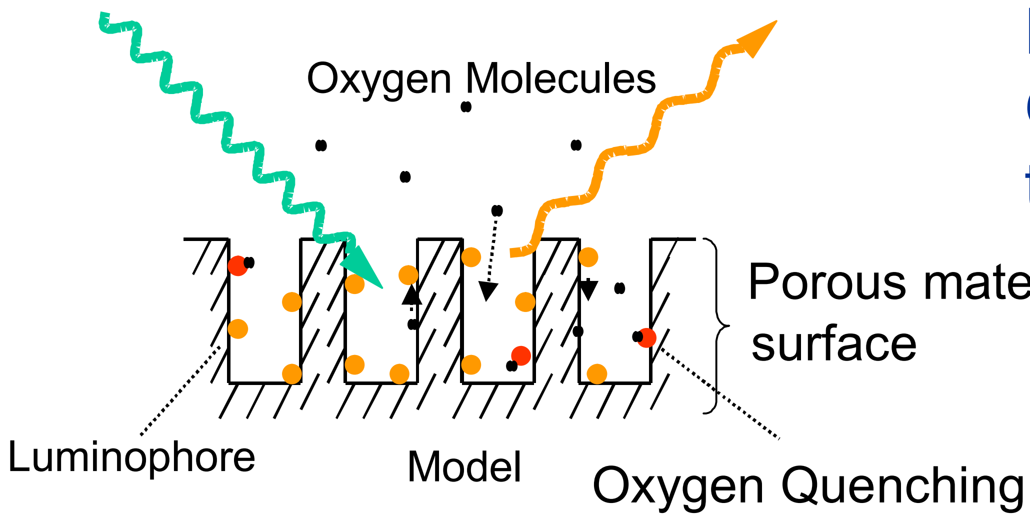
- To develop a nano-engineered exo-skeletal surface to overcome the limitations of gas diffusivity in conventional PSP coatings that will allow true dynamic surface pressure measurements. The open surface is a key component in the development of a “point and shoot” dynamic pressure measurement system to be used in aerospace testing applications.

Conventional versus porous PSP



Typical polymer PSP

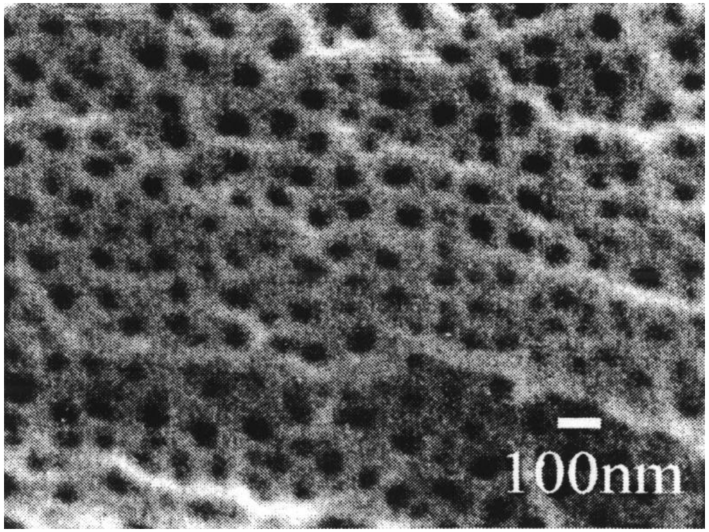
O_2 diffusion limits response



Porous, unsteady PSP

O2 quenching occurs at the surface

Types of porous surfaces

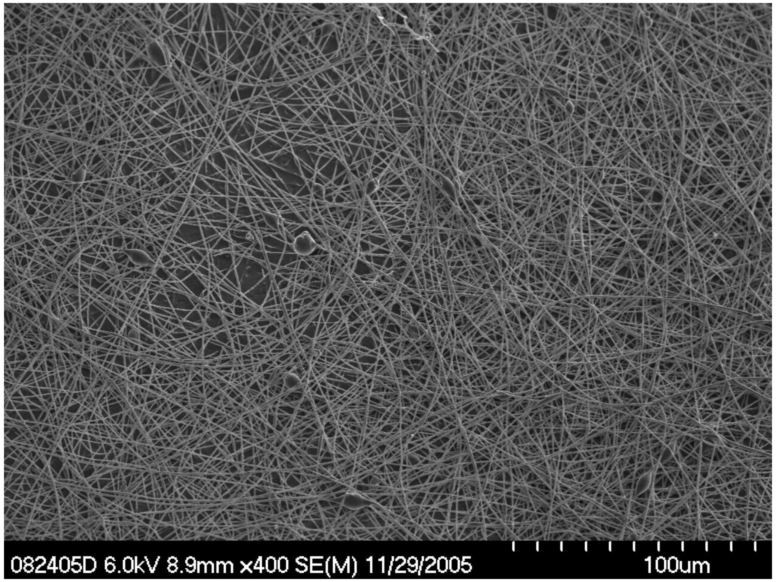


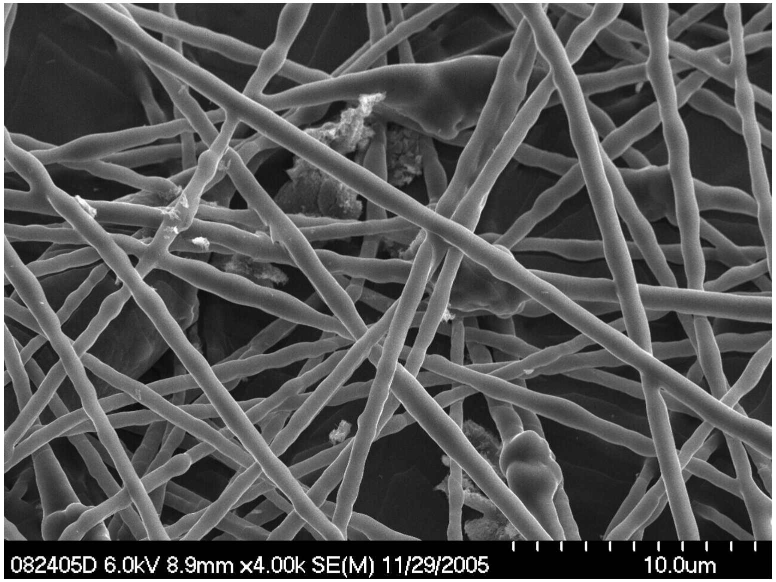
Response times of 40μS (25KHz) have been measured using shock tubes.
The system is impractical for most test articles

The anodized aluminum approach etches micropores into limited materials, in this case aluminum with the sample dipped in a solvent luminophore mixture. (Purdue)

Types of exo-skeletal surfaces

Create a porous surface by "weaving" an open weblike structure out of nanofibers and apply the oxygen sensor by spraying over the "fabric"

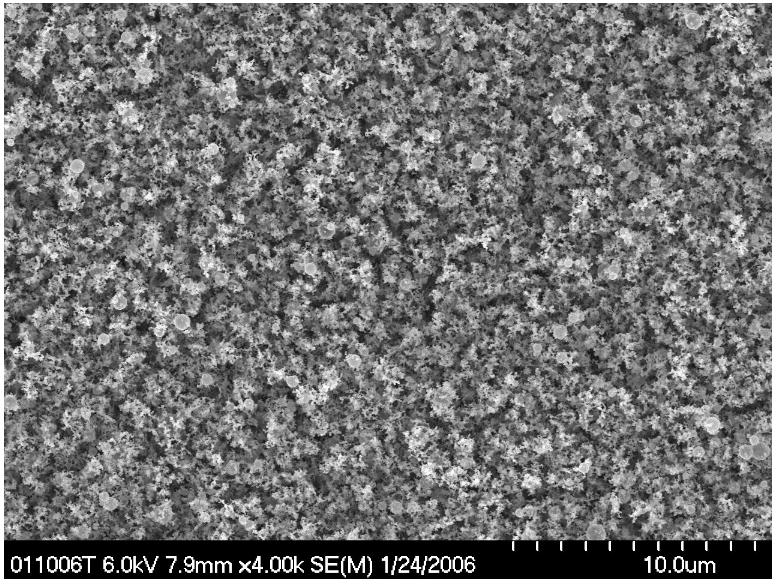


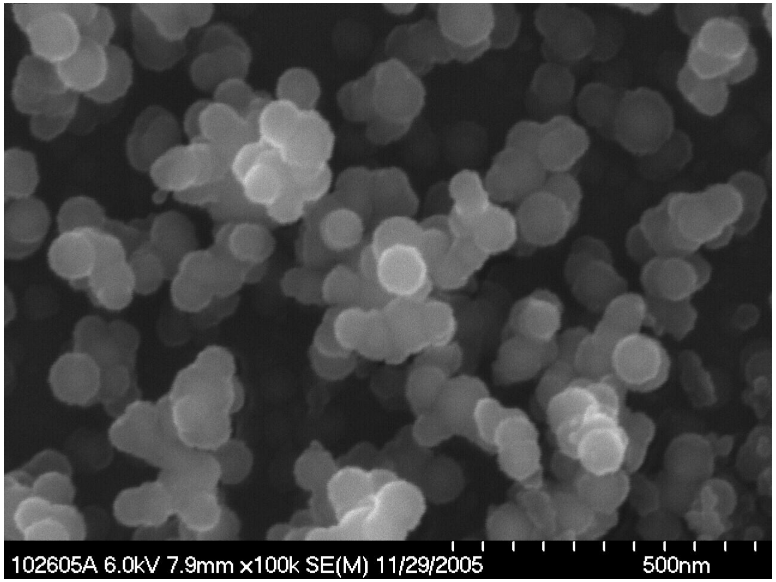


Electrospun PAN samples created at GRC

Types of porous surfaces

Create a porous surface by creating an oxide layer and apply the oxygen sensor by spraying over the film.

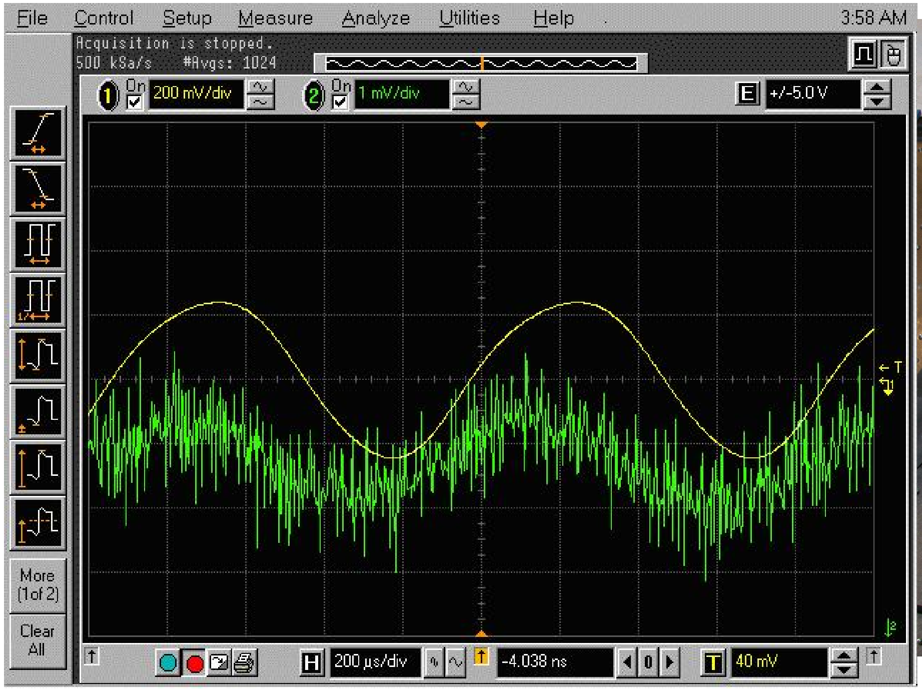




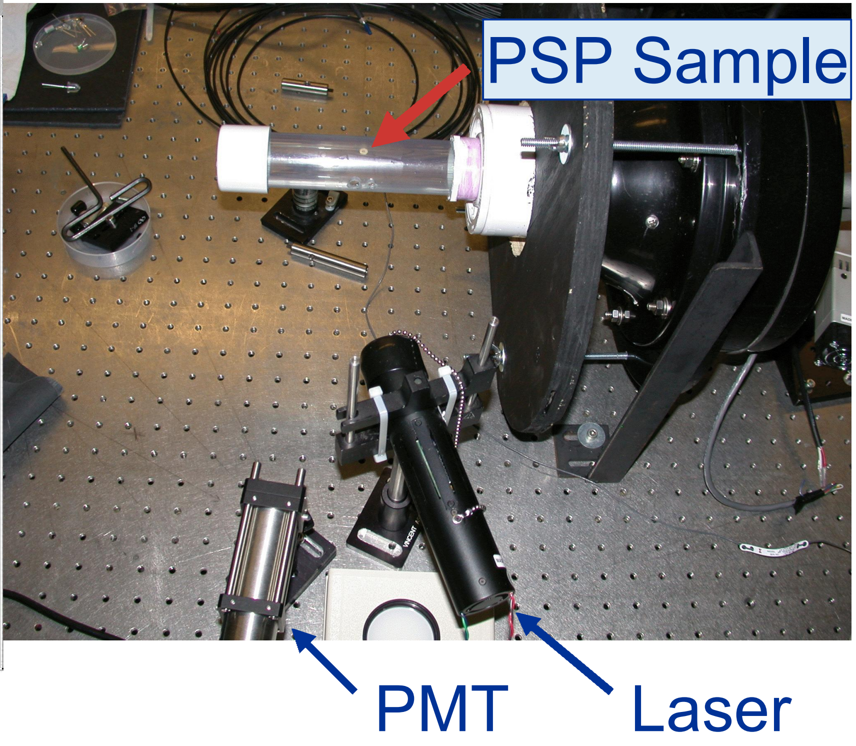
Flame synthesized TiO_2, as deposited directly upon the test coupon

Examples

PSP vs pressure transducer in a standing wave tube experiment used to characterize the frequency response of samples



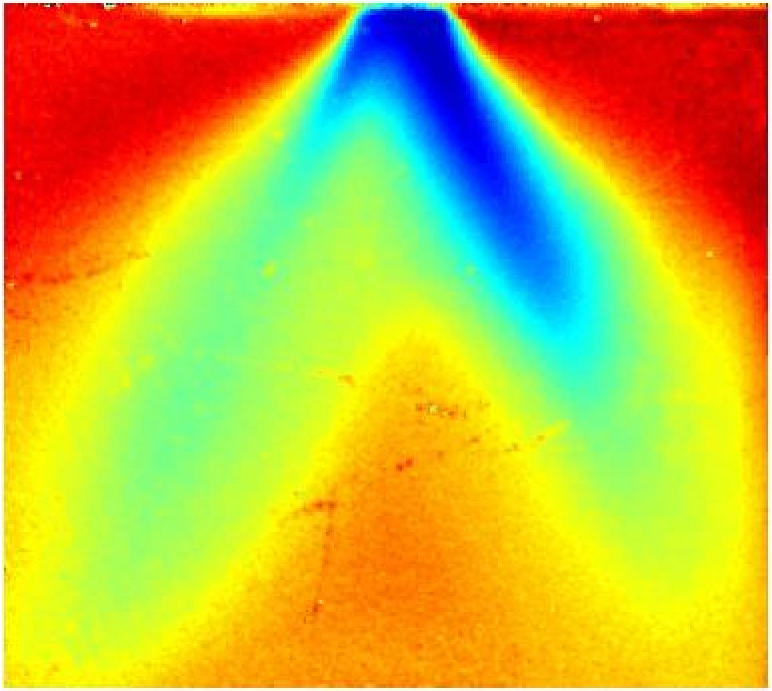
Solgel based PSP response at 1095 Hz (LaRC PSP)



Example

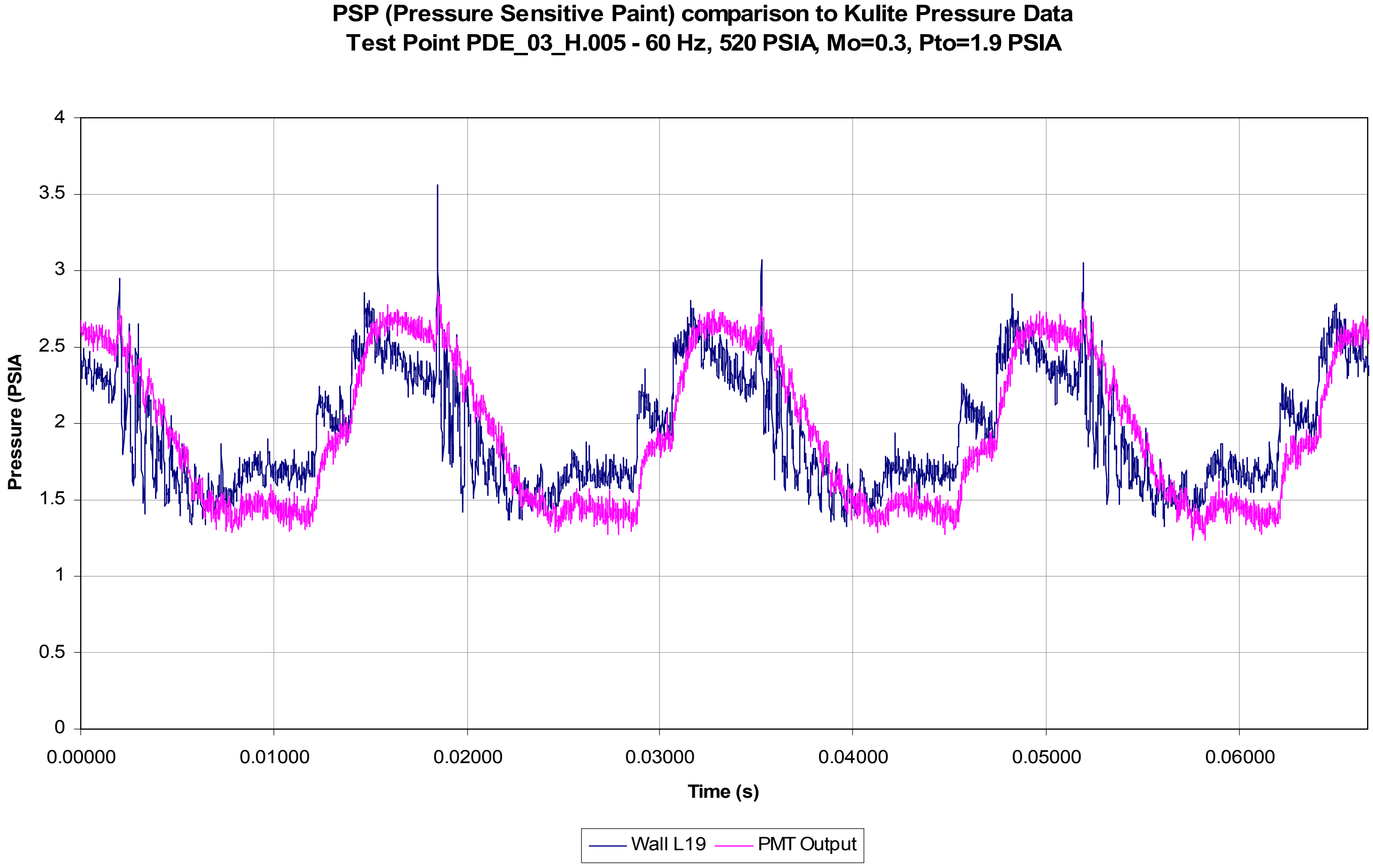
A fluidic oscillator is used to characterize the response of PSP samples. Here a polymer ceramic PSP is doped with RudpCl, frequencies of up to 8Khz can be tested with different gas mixtures (nitrogen jet)

t=0 μs

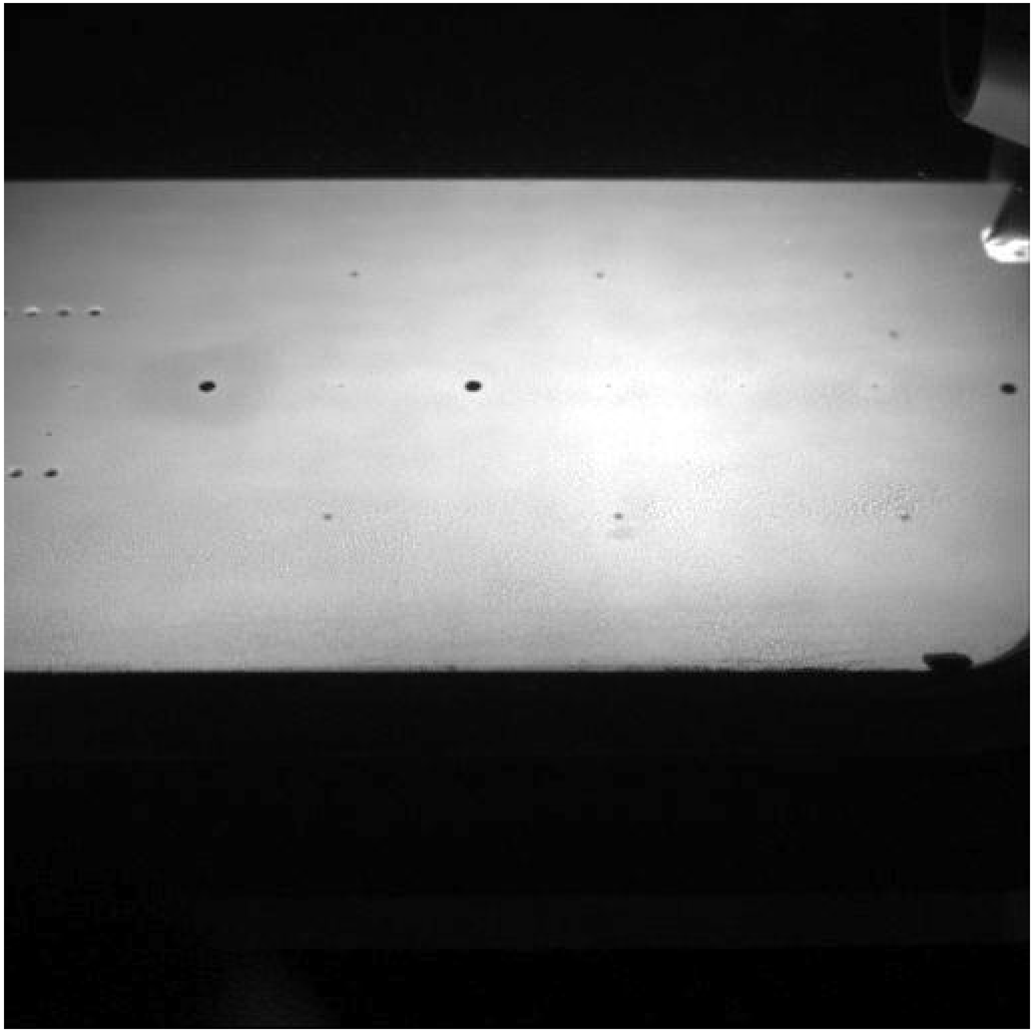


Examples

Pulse Detonation engine test in the 1X1 using a fast polymer PSP



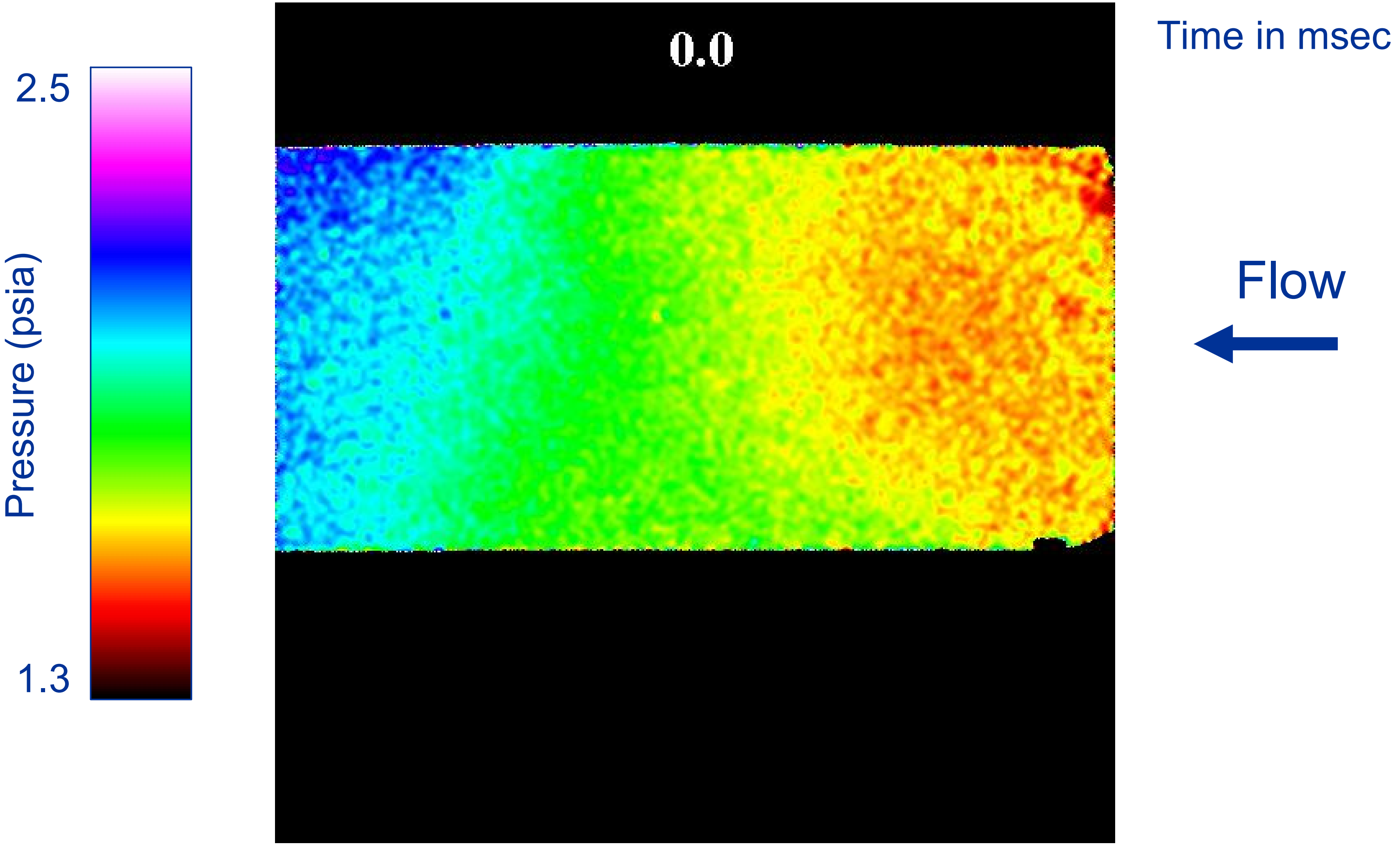
PDE Test 1X1



Flow

Camera view of sidewall from bottom

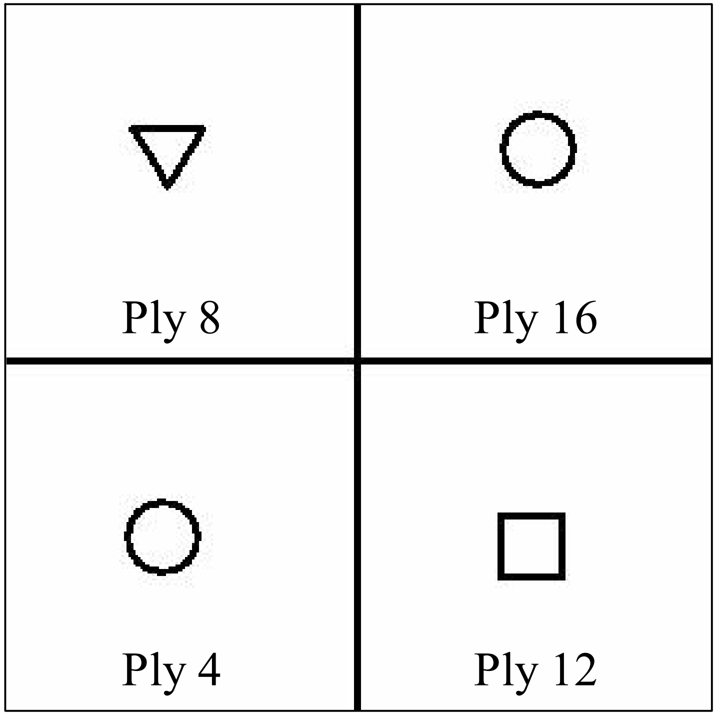
PDE Test 1X1 Data Point G005, 120Hz, 525 psi



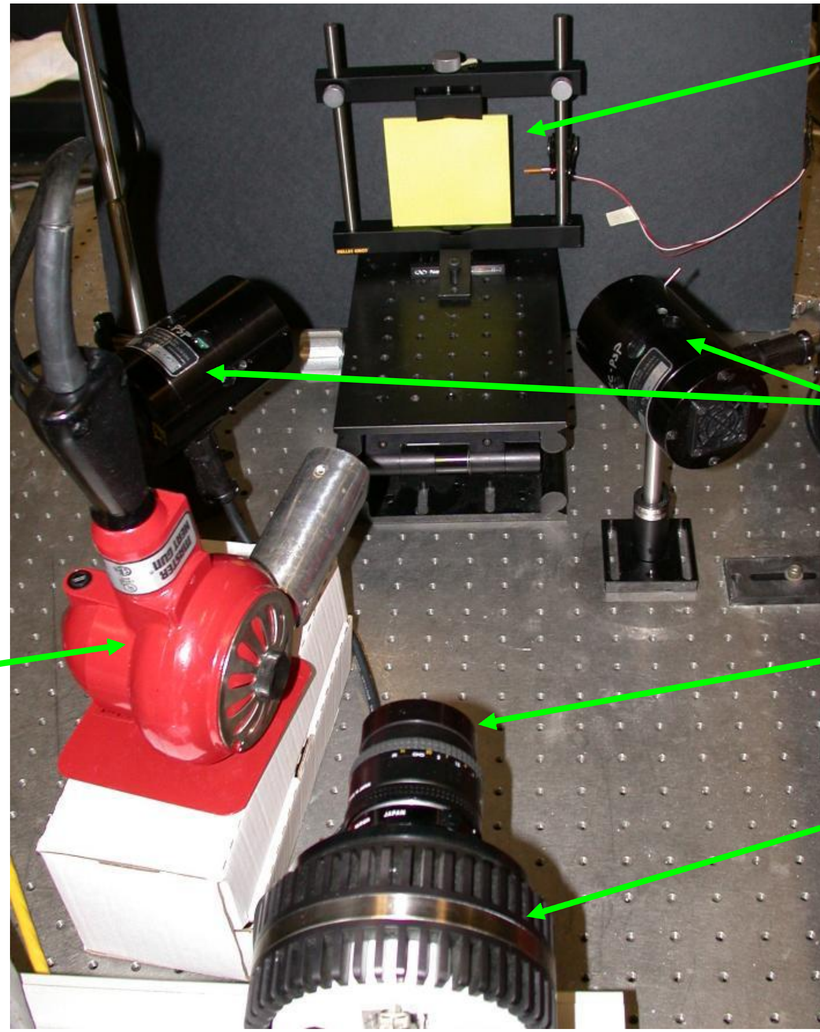
NDE Test sample

Carbon/Carbon composite with a converted SiC oxidation resistant coating

- 20 ply with artificial delaminations at various locations
- Length: 95.7mm
- Width: 95.7mm
- Thickness: 2.8mm
- Weight: 43.3g
- Coated with Boeing TSP



NDE Test setup using TSP coated sample



TSP coated sample

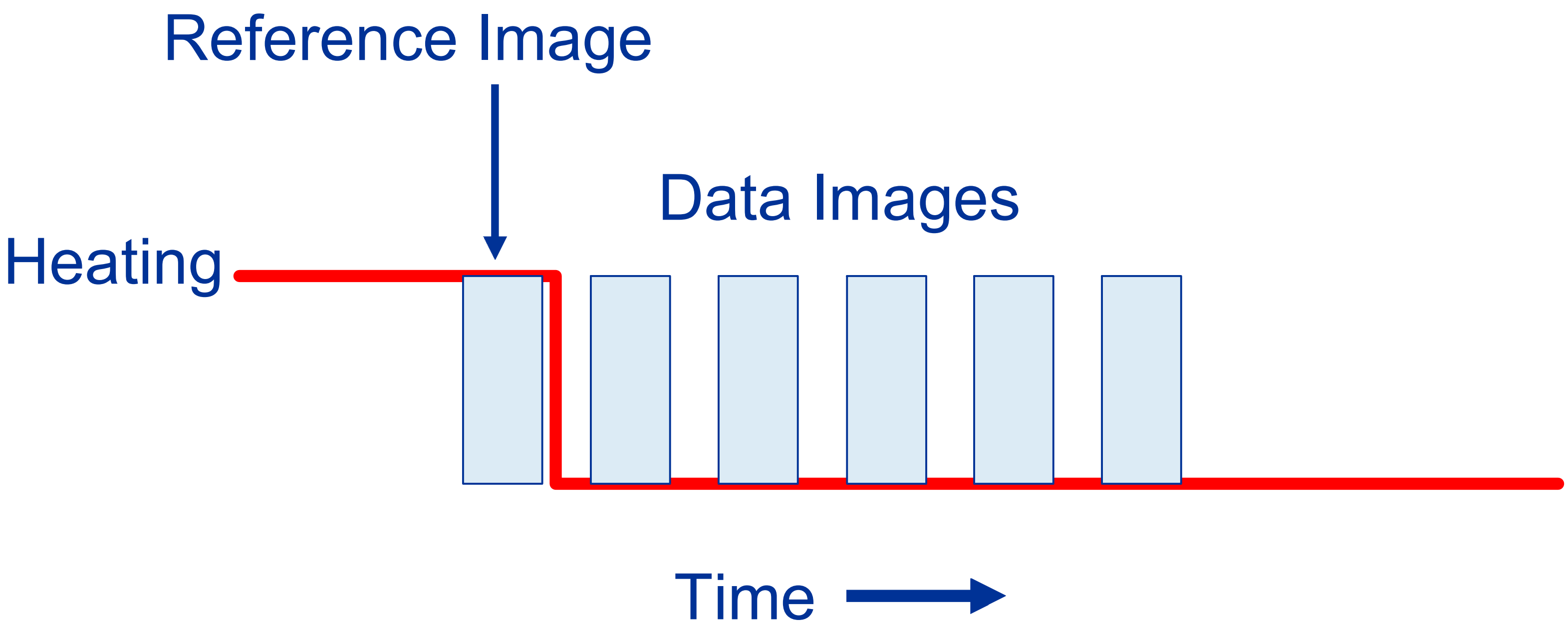
Blue LED Lights

Heat source

Filter: 520nm LP + IR

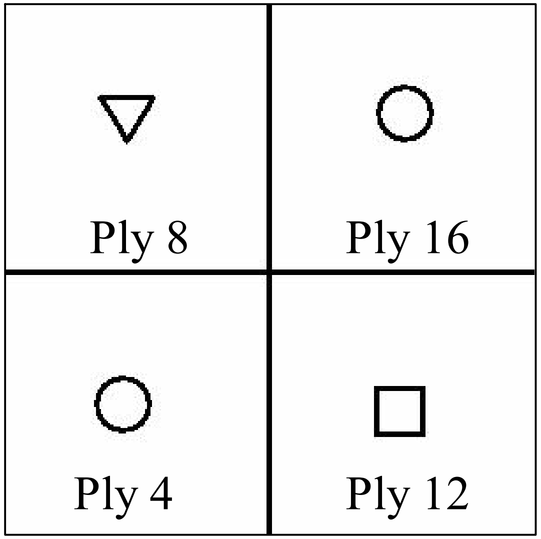
Camera

Detection of embedded flaws with TSP

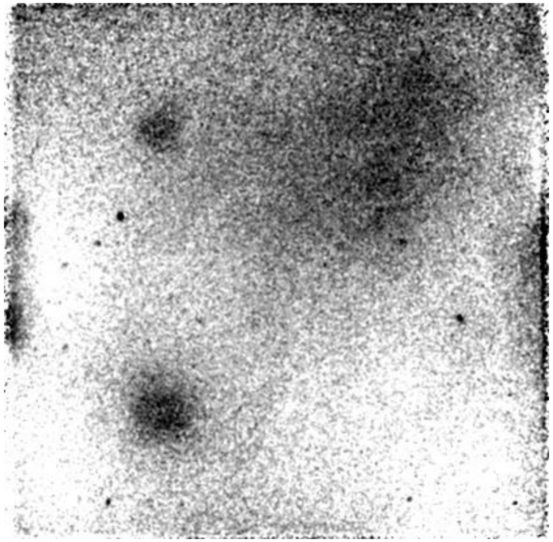


Pulsed heat source not available in short time frame
Determine flaws from cooling of material using long pulse method

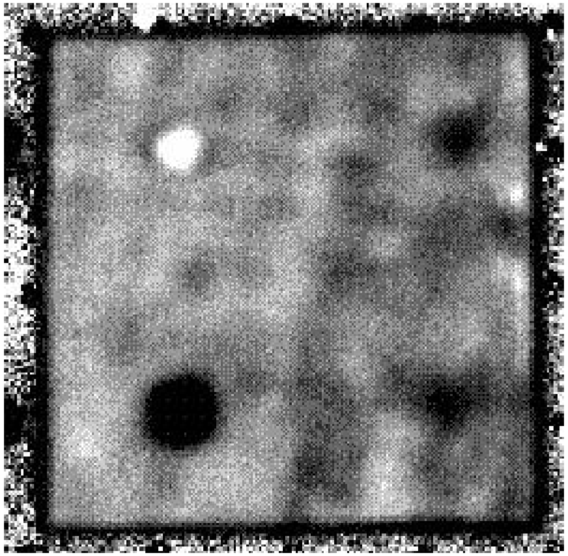
Detection of embedded flaws results



Embedded flaws



Detected flaws with TSP, exponential fit of cooling sequence



Detected flaws with Pulsed thermography, (derivative @328ms)

Detection of embedded flaws in the Carbon/carbon sample was possible using the TSP method for flaws closest to the surface in this crude test with minimal optimization.

Summary

- PSP senses O2 concentration in binder by setting up competition between quenching and emission.
- TSP similarly sets up competition between emission and non-radiative decay
- Oxygen permeable binder needed to apply paint, but increases temperature-sensitivity and degrades time response of PSP
- Porous surfaces are needed for true dynamic PSP response > 20KHz
- Several fast PSP coating concepts are being explored
- Unsteady temperature is possible but much lower rate < 100Hz